Assembling silver nanowires using optoelectronic tweezers

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Abstract:

Light patterned dielectrophoresis or optoelectronic tweezers (OET) has been proved to be an effective micromanipulation technology for cell separation, cell sorting and control of cell interactions. Apart from being useful for cell biology experiments, the capability of moving small objects accurately also makes OET an attractive technology for other micromanipulation applications. In particular, OET has the potential to be used for efficiently and accurately assembling small optoelectronic/electronic components into circuits. This approach could produce a step change in the size of the smallest components that are routinely assembled; down from the current smallest standard component size of 400×200 µm (0402 metric) to components a few microns across and even nanostructured components. In this work, we have demonstrated the use of OET to manipulate conductive silver nanowires into different patterns. The silver nanowires (typical diameter: 60 nm; typical length: 10 µm) were suspended in a 15 mS/m solution of KCL in water and manipulated by positive dielectrophoresis force generated by OET. A proof-of-concept demonstration was also made to prove the feasibility of using OET to manipulate silver nanowires to form a 150-µm-long conductive path between two isolated electrodes. It can be seen that the resistance between two electrodes was effectively brought down to around 700 Ω after the silver nanowires were assembled and the solution evaporated. Future work in this area will focus on increasing the conductivity of these tracks, encapsulating the assembled silver nanowires to prevent silver oxidation and provide mechanical protection, which can be achieved via 3D printing and inkjet printing technology.

Introduction:

The main technology to assemble electronic circuit at present is known as surface-mount technology (SMT), which uses a robotic arm with a vacuum tip to pick up and place discrete electronic components onto the surface of printed circuit boards. In order to produce a step change in the size of the smallest components (400×200 µm, 0402 metric) that can be handled using SMT technology down to a few microns and even nanostructured components, we reported the use of a radically new assembly strategy based on a touch-less opto-electro-fluidic technique known as optoelectronic tweezers (OET). OET is an emerging technology that uses light-controlled dielectrophoresis (DEP) force to effectively manipulate micro-objects such as cells [1]-[4]. As shown in Fig.1, a typical OET device consists of two electrodes made of indium tin oxide (ITO) coated glass slides which form a sample chamber. The bottom electrodes is further coated with a layer of photoconductive semiconductor material, typically amorphous silicon (a-Si:H). A liquid buffer containing experiment samples is placed between the two electrodes, which are connected to a function generator. In the dark, the impedance of the photoconductive layer is very high and most of the voltage is dropped across the photoconductive layer. Where a light pattern is imaged onto the photoconductive layer, the impedance of this layer drops significantly and the voltage is dropped into the liquid surrounding the illuminated area, creating a non-uniform electrical field between the two electrodes. For the polarizable samples in the liquid, a dipole is induced in the object, which interacts with the non-uniform electrical field. When an object with larger polarizability than the solvent interacts with the non-uniform field, it is attracted to the region of highest field (positive DEP force); while for an object of lower polarizability than the solvent, the object is pushed away from the region of highest field (negative DEP force). Therefore, by controlling the position of illumination region in the OET device, 'traps' can be created to manipulate the position of samples. The DEP force created in an OET device for an ideal spherical particle is given by $F = 2\pi r^3 \varepsilon_m \mathrm{Re}[k(\omega)]\nabla E^2$, where r is radius of the particle, ε_m is the permittivity of the medium, $\mathrm{Re}[k(\omega)]$ is the real part of Clausius-Mossotti (CM) factor and ∇E^2 is the gradient of the electric field squared [5].

Compared with optical tweezers (OT), OET traps have been found to be 470 times stiffer for a similar light intensity [6] and capable of massively manipulation of cells and micro-particles in parallel [1]. Therefore, such advantages also make it an ideal approach for massively assembly of metallic particles and components in to circuits. In this work, we present the results of successful assembly of silver nanowires by positive DEP force using a specifically-designed OET device. Silver nanowires were assembled to form a 150-µm-long conductive path to link two isolated metal electrodes, which effectively brought down the resistance between the two electrodes to around 700 Ω. In the

following, we first describe the fabrication of OET device with isolated metal electrodes. Then, we demonstrate the controlled assembly of silver nanowires between the isolated electrodes and finally, preliminary electrical characterization of the device and discussion are given.

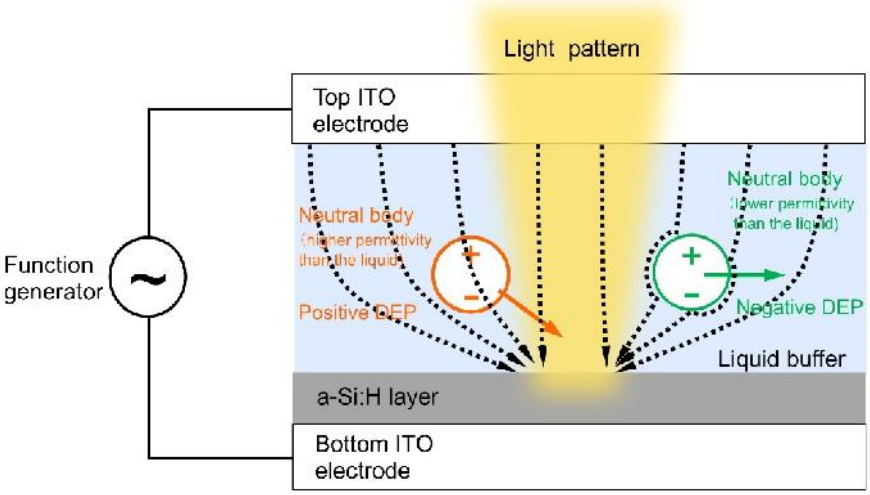

Fig.1: Schematic of an OET device. The light pattern creates a non-uniform electrical field, resulting in the attracting or pushing way of the particles depending on their permittivities.

Device Fabrication, experimental setup and samples:

The two electrodes used for our OET device are ITO-coated glass slides (Diamond Coatings, UK) with a thickness of 600 nm [7]. The photoconductive layer used in our OET device is a-Si:H, which is deposited on top of ITO coated glass at a thickness of 1 µm by plasma-enhanced chemical vapour deposition (PECVD) at 300 ºC. Then a 350 nm thickness SiO_2 was deposited on top of the a-Si:H. After this, typical photolithography was used to define the pattern of metal electrodes, followed by selective etching the SiO_2 layer using reactive-ion etching (RIE) to expose the a-Si:H and define the mesa structure of metal electrodes. Finally, photolithography was used again to define the pattern of the metal electrodes followed by metal deposition of 20nm/100nm Ti/Au layer using electron-beam evaporator and metal lift-off in acetone. Fig.2 (a) and (b) shows a schematic cross-section and a top-view image of the fabricated OET device with metal electrodes. The reason of the use of SiO_2 layer will be discussed in the following section. As shown in Fig. (b), there are six pairs of metal electrodes and each has a 3×3 mm^2 squared pad and 200 µm-wide metal track. The distances between the tracks are 500 µm, 400 µm, 300 µm, 200 µm, 150 µm, 100 µmand 50 µm (from right to left). A microscope image of the tracks with 150 µm distance is shown in Fig. (c). To bias the device, part of the a-Si:H at the edge of the device is removed to expose the conductive ITO layer, which is then mounted with a wire using silver paint and epoxy.

The experimental setup mainly consists of a microscope (Olympus BX51), a digital micro-mirror device (DMD) projector (Dell 1510X), a Camera (Olympus UC30), a function generator (TG 5011 LX1), an amplifier (Thurlby Thandor Instrument WA31) and a PC. The schematic of the projection system is shown in Fig.3.

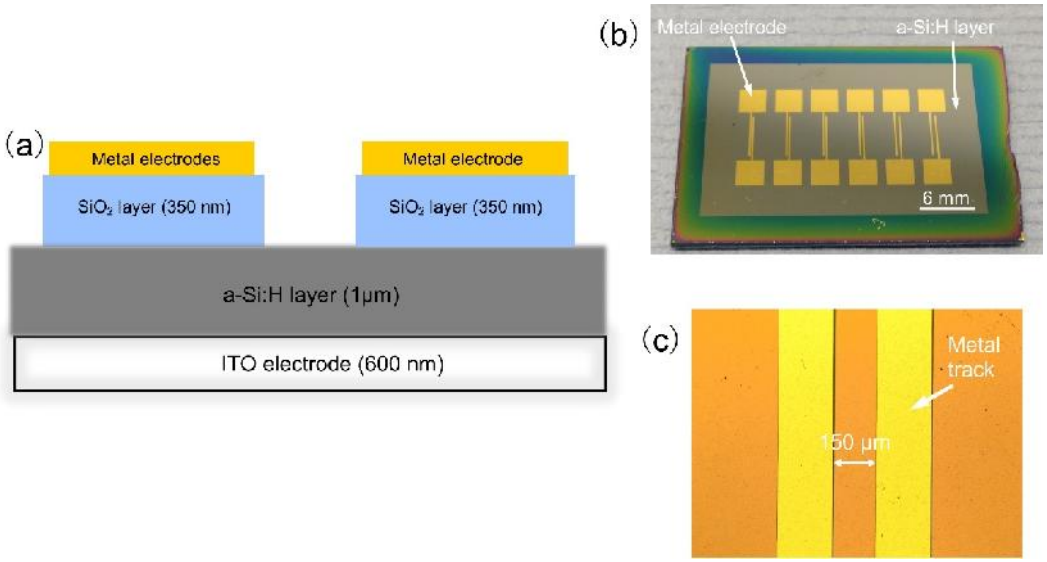

Fig.2: (a) Schematic cross-section of the OET device with metal electrodes; (b) top-view image of the completed OET device; (c) microscope image of metal tracks with a distance of 150 µm.

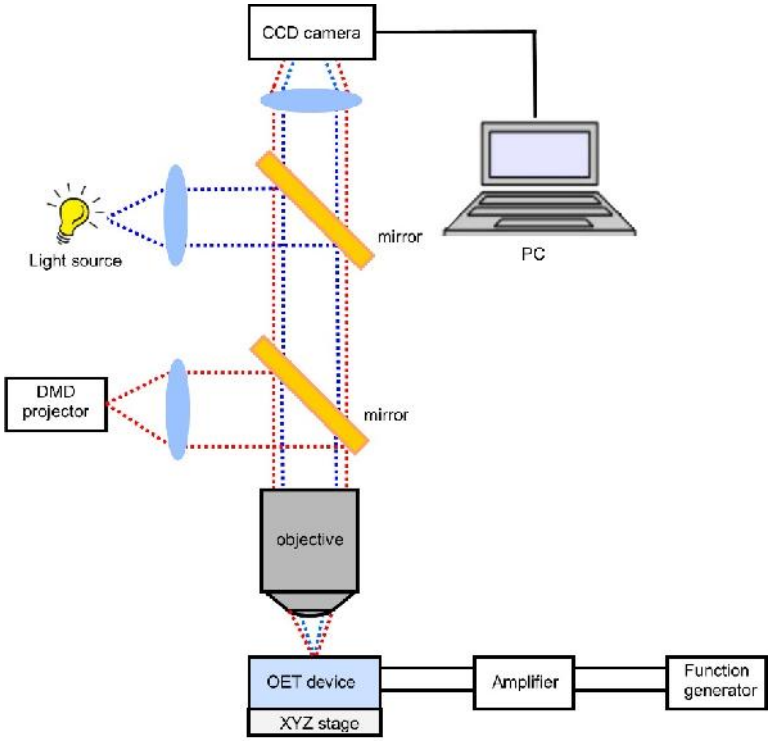

Fig.3: Schematic setup of the experimental setup.

The silver nanowires used in this work have a typical diameter of 60 nm and typical length of 10 µm (739421 Aldrich). Fig. 4 shows the Scanning Electron Microscopy (SEM) images of silver nanowires at different magnifications. These images verify the approximate dimensions of each nanowire. It is also seen that the nanowires have a tendency to 'clump together' in unorganised complexes. This may be reduced simply shaking and mixing the solution thoroughly prior to experiment or by the introduction of a surfactant which will break down some of the nanowire clumps. In our work, the surfactant 'Tween' is used at a volume ratio of 0.05% to minimise the nanowire clumps.

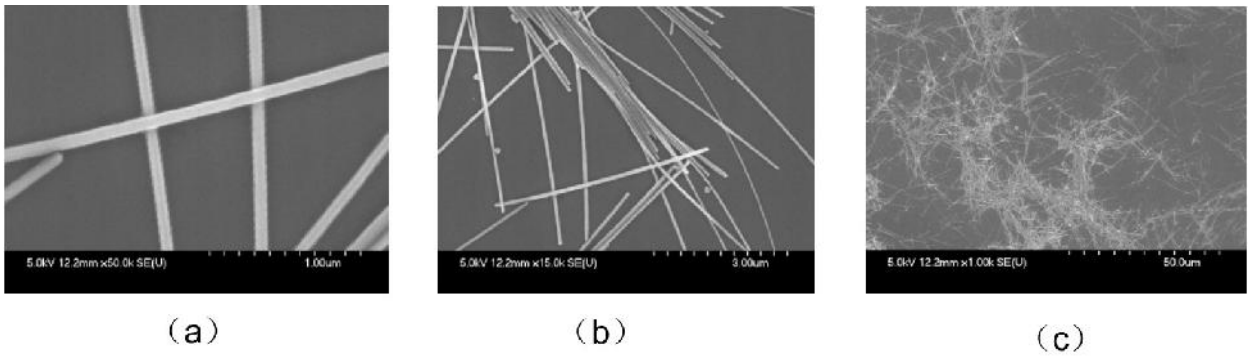

Fig.4: Three SEM images of silver nanowires in solution at (a) 50000x, (b)15000x, and (c) 1000x magnification.

Experimental results:

The silver nanowires used in this work were initially suspended in isopropanol at a concentration of 0.5%, as provided by the company. To make the sample for OET experiment, we diluted the 'native' nanowire solution to potassium chloride (KCL) water solution at a volume ratio of 1:10. The conductivity of KCL solution was $10mSm^{-1}$. In order to minimise the clumps of nanowires, a recommended concentration of 0.05% Tween was also added to the sample [8]. The conductivity of sample increased from $10mSm^{-1}$ to $15mSm^{-1}$ after adding the Tween, which is suitable for manipulating silver nanowires. Finally, the nanowire solution was pipetted into the OET device. After adding an AC voltage across the OET device and projecting light pattern onto its photoconductive layer, the silver nanowires were assembled according to the shape of the light pattern. In order to analyse the experimental results, we used an image processing software to calculate the mean grey value, which represents the effectiveness of the assembling process [9].

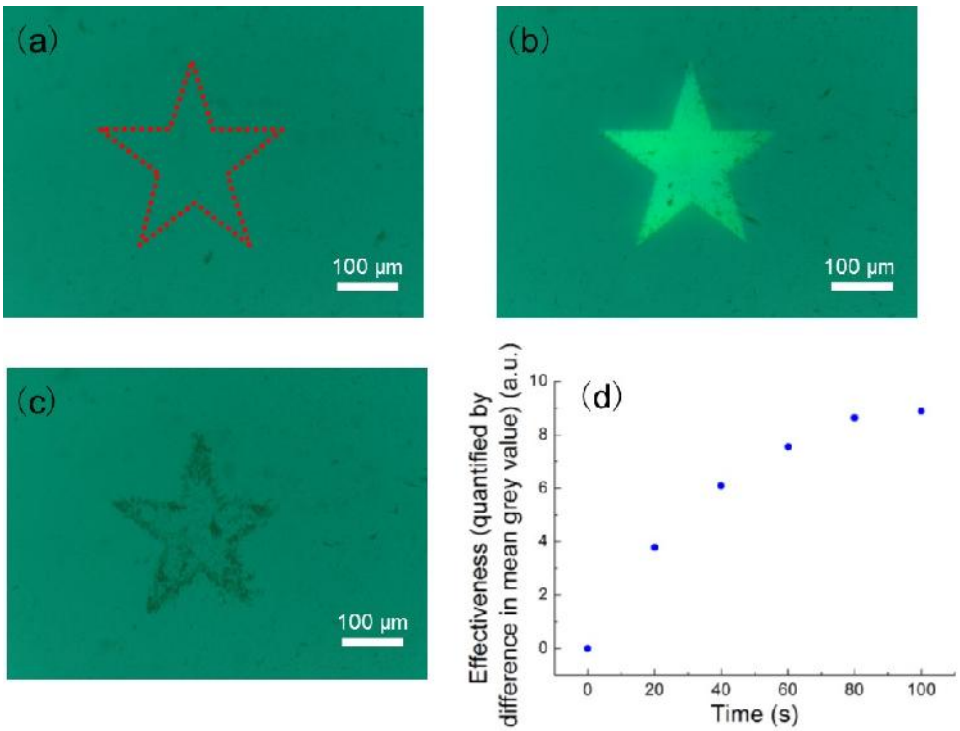

Fig.5: Microscope images of silver nanowires (a) before, (b) during and (c) after the assembling by a star-shape light pattern in OET device; (d) Effectiveness of the assembling of silver nanowires with time, which is quantified by the difference in mean grey value of the assembled pattern.

Fig.5 (a)-(c) show the microscope images of silver nanowires before and after being assembled using a star shaped light pattern. A 30 kHz 30V peak-to-peak AC voltage was used to provide the electric potential across the device. It can be seen that the nanowires experience positive DEP force and is attracted to the light pattern accordingly. This result is similar to previously reported work [10]-[13]. The silver nanowires have very high conductivity, making the CM factor positive and thus a positive DEP force is expected. Fig.5 (d) shows the effectiveness of the assembling of silver nanowires of the triangular area (marked by red dotted line in Fig.5 (a)) as a function of assembling time, which is quantified by the difference in mean grey value. As shown, the effectiveness increases with the increase of time. However, the increase of effectiveness is more prominent at the beginning and slows down with the increase of time. After 80s, the assembled nanowire pattern remains stable and the effectiveness saturates, meaning that few nanowires can be attracted to the light pattern. This is due to the fact that the DEP force is only functional for the nanowires in a certain area. After a certain amount of time, the nanowires in this functional area are all attracted and further increasing the assembling time will not make a huge difference to the effectiveness of the assembled pattern. Additionally, the assembled nanowire pattern can block some of the light pattern, thus weakening the DEP force and the ongoing assembling process. As shown in Fig. 5(c), for the assembled nanowires, it is more likely to be attracted to the edge of the light pattern, which is due to the larger gradient of the non-uniform electrical field at the edge compared with the central area. In terms of the overall performance of the assembling, the assembled nanowire pattern is very similar to the light pattern and the main assembling process finished in 80 seconds, indicating very strong DEP force generated by the OET device to silver nanowires. This strong DEP force is due to the high polarizability of silver nanowire and its high CM factor. More details of the DEP force generated by OET device to individual silver nanowire can be found elsewhere [10]. In this work, AC voltage with different frequencies were also used to bias the OET device (10 kHz, 20 kHz and 50 kHz) and the assembling results are similar to that using 30 kHz AC voltage.

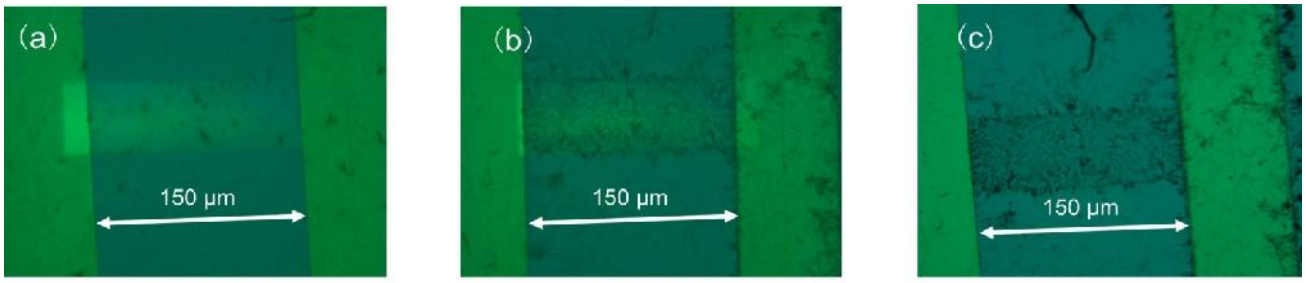

Fig.6: (a) microscope image of nanowires moving to the light pattern; (b) microscope image of nanowires being assembled to the light pattern after OET device in operation for 1 minute; (c) conductive path between 150-µm metal electrodes formed by silver nanowires after evaporating the solution.

Fig.6 (a) shows the silver nanowires being assembled by a rectangular light pattern in the OET device to link two isolated metal electrodes. The distance between the two electrodes is 150 µm. After assembling the nanowires for 2 minutes, the nanowire pattern is formed, as shown in Fig.6 (b). Then the OET device was put on top of a hotplate for five minutes at 100 ºC to evaporate the solution. The evaporation of the solution doesn't influence the nanowire pattern significantly with no apparent loss of nanowires on drying. After evaporating the solution, the current-voltage (I-V) characteristic of the two electrodes were measured by a semiconductor device analyser (KEYSIGHT B1500A). Fig.7 shows the I-V characteristics of the two electrodes before and after assembling the nanowires. Before assembling, the resistance between the two electrodes are quite high ($10^8\Omega$). It is worth mentioning that there is a 350 nm thick SiO_2

layer sandwiched in between the metal electrodes and a-Si:H layer. Without the SiO_2 layer, the resistance between the electrodes is quite low, suggesting that they are short-circuited. This may be due to pin holes in the a-Si:H layer, which could create a connection between the metal and ITO layer after metal deposition. Therefore, the SiO_2 layer in the OET device functions as a passivation layer to prevent the metal electrodes being short-circuited. As shown in Fig.7, a liner I-V curve was achieved and the resistance between the two electrodes was effectively brought down to around 700 Ω after assembling the nanowire pattern. This proves that the silver nanowires can be effectively assembled by OET to create a conductive path to link the isolated electrodes, which is meaningful for further assembling small electronic and optoelectronic device into circuits. Future work in this area will focus on further increasing the conductivity of silver nanowire pattern as it's resistance will have to be reduced to a few Ohms to be of use for making electrical contacts between electronic components, encapsulating the assembled silver nanowire pattern to prevent oxidation and provide mechanical protection, which can be implemented via 3D printing and inkjet printing technology.

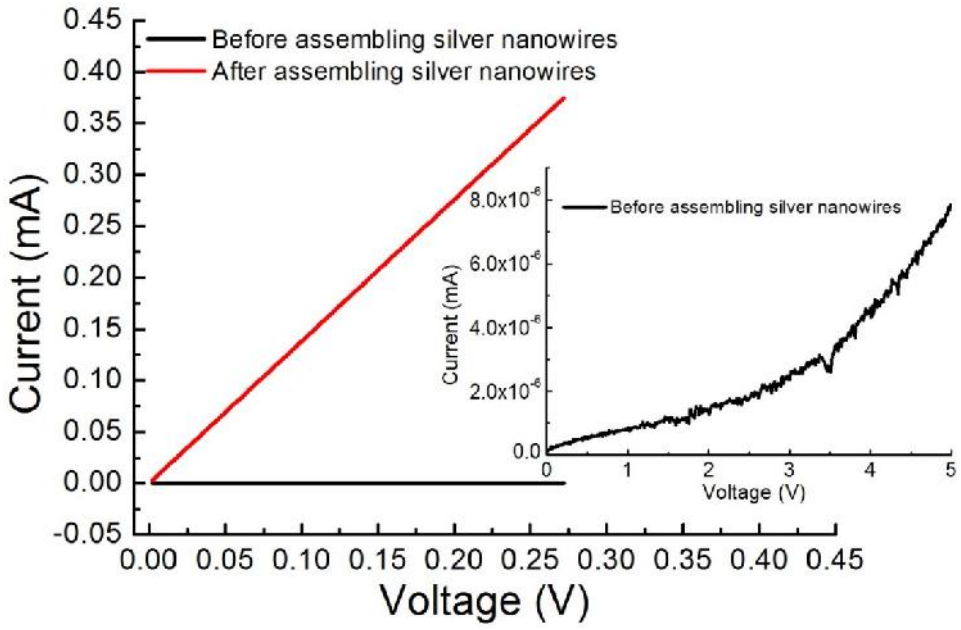

Fig.7: I-V characteristics of two isolated metal electrodes before and after assembling the silver nanowires. The inset shows the detailed I-V characteristic of the metal electrodes before assembling silver nanowires.

Conclusion:

In this work, we demonstrate the use of a specifically-designed OET device to assemble silver nanowires into conductive path to link two isolated metal electrodes with 150-µm distance. The resistance of the electrodes were effectively brought down to around 700Ω after assembling the silver nanowires. Additionally, silver nanowires demonstrated very good performance in OET device, such as short assembling time and strong DEP response. This work demonstrates the potential of using OET to assemble silver nanowire pattern, which is very meaningful for micro-sized circuit construction.

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